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# Validation of the AVM Blast Computational Modeling and Simulation Tool Set

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## ABSTRACT

*Protection of US military vehicles and its occupants against landmine and IED threats remains an important concern in the area of defense research. Traditionally, military vehicles are designed and developed based on many component and full vehicle tests. Defense Advanced Research Projects Agency (DARPA) funded the Adaptive Vehicle Make (AVM) portfolio of programs that developed a set of tools and processes whose goal was to reduce the cost and development time for cyber physical design by a factor of five, while expanding design adaptability and predictability of performance. In order to achieve this goal, the AVM portfolio developed many tools, methodologies and processes. One of the most important tools developed in the AVM program is the survivability assessment tool-Blast Computational Modeling and Simulation (BCMS) toolset. The BCMS can speed up the survivability performance assessment of a ground vehicle system significantly. This paper describes the capability of the AVM BCMS tool suite and to validate the suite using the three series of physical live fire tests.*

*For simplified structures, like a rigid plate, and a deformable plate, the AVM BCMS prediction agrees well with the live fire test measurements. The prediction accuracy is within 17%. In a more complicated structure case such as a blast box, the accuracy of the response predictions using AVM Blast M&S Toolset is decreased. In general, the tool suite overestimates the deformation of a complicated structure. Based on this study, authors believe that the concentrated blast load distribution causes the over-estimation of the structure deformation. Because target structure deformation is over estimated, the more energy is consumed on structure deformation, and the initial velocity as well as the jump height of the target structure is under estimated. This hypothesis needs to be further validated by using live fire tests and more detailed studies.*

## INTRODUCTION

Protection of US Army vehicles and soldiers against landmine and IED threats remains an important concern in the area of defense research. Traditionally, military vehicles are designed and developed based on many component and full vehicle tests. The scope of this process can be found in the Integrated Defense Acquisition, Technology, & Logistics Life Cycle Management Framework. One of the big challenges associated with these processes is the craftsmen-like nature of building these complex cyber-mechanical systems. One typical approach is to break the system into subsystems and have separate teams embark on building the individual subsystems and optimize them for size, weight, and power. Once the subsystems reach a reasonable level of development, an integration effort takes place to tie the subsystems together. The system is then tested against requirements which are rarely met on the first integration-testing cycle. The steps will then be iterated until the system meets its requirements. [1-6]

This is a costly approach, especially compared with something like computer chip production. Intel, for instance, has an excellent track record in getting systems right in the design phase so that extensive testing and integration are not needed. This "correct-by-construction" methodology is powerful and would not be possible without high-level design languages to support validation and verification. [1,4]

The Defense Advanced Research Projects Agency (DARPA) launched an ambitious Adaptive Vehicle Make (AVM) program to reduce the time it takes a military ground vehicle to go from concept to production by a factor of five. The goal of the AVM portfolio was to move to this model for building large, complex, heterogeneous cyber-mechanical systems for increased cost and schedule efficiencies. An important part of this program is accurate

modeling of vehicle systems' behaviors, with the goal that the vehicle be "correct by construction."

The AVM process attempts to raise the level of abstraction in the design process, consciously giving up component-level optimality in exchange for ease of verification, decoupling design and fabrication, and utilizing a flexible foundry method of manufacturing. To accomplish this task, a new process has been developed, and a set of tools constructed that promise to:

- Raise the level of abstraction such that the designer need not manipulate the design at the lowest numbered part level, but can operate at varying levels of hierarchical abstraction and model fidelity early on in the design process and prior to source selection.
- Develop practical and observable metrics to describe complexity, as well as the traditional metrics for size, weight, power, and performance, to enable the making of informed design decisions.
- Enable rapid exploration of the design trade-space for high-fidelity requirements tradeoffs.

In summary, the AVM paradigm shifts the focus from optimizing the design at the component level through testing and validation to a more system-level optimization approach that relies on a less accurate model-based approach to component design. This approach is most useful during the source selection process, while the contract is still open and prior to a more detailed design by the winning contractor.

DARPA's Adaptive Vehicle Make portfolio, or AVM, is a suite of interlocking programs that are designed to enhance the adaptability of our military forces by compressing the development timelines for complex defense systems by at least five times. A brief description of each of the tool sets is given here:

### *A. Generic Modeling Environment (GME)*

Generic modeling environment (GME) is a simulation software creation interface tool set that provides the foundation of all AVM design and simulation toolsets. Its purpose is to provide an environment to construct multiple physics domain models of large-scale engineering systems. GME paradigms are produced from formal modeling environment specifications, which define how systems in the domain are modeled [2].

The GME paradigm produced here is Meta CyPhy. The Meta CyPhy paradigm defines the interfaces between components. All vehicle system components from the component library must interface neatly with the Meta CyPhy paradigm's requirements for such entities. Properties, parameters, and connections are all defined in such a way to provide consistent interface definitions and guidelines, making the framework consistent with a ground vehicle system design.

### *B. META-link/HuDAT – CAD Interface*

It is well known that CAD software is necessary to create a unique configuration component such as a hull of a ground vehicle system. In AVM Meta CyPhy, Creo has been chosen as the CAD software to interface directly with GME and CyPhy. After a CAD model is generated, it must be imported into GME/CyPhy where it is given additional properties and parameters to fully characterize that component. Using the hull as an example, material properties and manufacturing metrics must be defined before things such as weight, center of gravity (CG) and manufacturing costs can be computed. This importing of the CAD model can be accomplished using a tool known as META-link. META-link is a tool providing simple importing functions from CAD to CyPhy and vice versa.

In addition to META-link, a tool known as HuDAT has been developed that also provides a link between CyPhy and CAD. This tool is specifically developed for hull design, and streamlines the process of generating complete hull assemblies within CyPhy, while quickly generating manufacturing properties and parameters necessary to describe the welds between hull component plates.

### *C. Test Benches*

Simulations are performed within the framework of a test bench. A test bench is a simulation that predicts the performance of a design at the system level. A suite of test benches is included with each seed design that consists of several individual test benches. Each test bench simulation has its own unique physics associated with it, and is typically tied in to a specific ground system requirement. Some test benches leverage Modelica to compute results, while others must rely on more specific software applications such as Abaqus, OpenFOAM, and LS-DYNA. In some situations, such as for blast and ballistics simulations, 3rd party software tools have been developed that interface directly with GME/CyPhy through these test benches.

### *D. SWRI Blast Simulation Test Bench*

The blast simulation test bench is developed by subject matter experts (SMEs) from the Southwest Research Institute (SwRI) to assess the performance of a designed ground vehicle system in response to a variety of mine blast threats. Mine blast loading conditions simulate the impulse delivered to a vehicle when subject to landmines or improvised explosive devices. To execute the test bench, a

component or model must be selected for simulation and the blast configuration defined. The test bench is classified into five tiers, depending on the desired fidelity of the target ground vehicle system responses, which are described here [3]:

- Tier 1: Blast simulation in Tier 1 treats the entire vehicle as a rigid, non-deformable body and calculates the vertical and horizontal velocities and maximum jump height due to the blast. This calculation can be accomplished in a few minutes and is intended for experimenting with the overall shape of the undercarriage of the hull, e.g. V-hull, double-V-hull, etc.
- Tier 2: Modeling in this tier takes into account the deformable nature of vehicle components and structural members but saves significant processing time by not accounting for the case when one deforming material contacts another one and continues to deform. The duration of this calculation can be as short as a few minutes and as long as many hours.
- Tiers 3: Blast simulation in Tiers uses LS-DYNA, a commercial finite element (FE) analysis code that accounts for contact between vehicle components. The finite element size in this tier is 30 mm. The duration of these computations is measured in many hours to days.
- Tiers 4: The modeling of blast events in tier 4 uses LS-Dyna and refined finite element meshes of 15 mm. The refined meshes provide higher fidelity of structural responses during the blast loading.
- Tier 5 The simulation in Tier 5 also uses a 15 mm resolution mesh and includes anthropomorphic test dummies (ATDs) to simulate the blast response on the human occupants of the vehicle.

## THE BCMS TOOL SET

The blast computational simulation tool set in the AVM Blast Test Bench is extracted and used independently to the other tool sets of the AVM tool suites. This Blast Test Bench is given a name of blast computational modeling and simulation (BCMS) for its standalone version. As stated earlier, the blast computational modeling and simulation tool set was developed at Southwest Research Institute under the DARPA AVM effort. The BCMS is a semi-empirical blast loading model. The tool set has three major modules: CONWEP model, the scale-factors-table calculator (SFTC), and LoadDyna.

The CONWEP module calculates the blast loads acting normal to each element with a blast segment for each time step. The blast loading on a single element was modeled using the *LOAD_BLAST_ENHANCED keyword (in LS-Dyna) for charge masses of 2 and 2000 kg. This keyword allows the user to specify the equivalent TNT mass of a blast charge, its x-, y-, and -z coordinates, and the time of the explosion. A blast segment consists of either four unique nodes (i.e. a quadrilateral) or three unique nodes (i.e. a triangle). A triangle is defined in the same way as a quadrilateral, but the third and fourth node indices are identical. The segment normal depends on the node order according to the right hand rule; the normal projects outward from the loop for which the nodes are defined in the counterclockwise direction. For direct loading, in which the blast pressure wave reflects off an element, the segment normal should point toward the blast location. For each blast segment, CONWEP first calculates six individual blast parameters, which depend only on scaled distance. Once the blast parameters have been determined, CONWEP calculates the reflected or incident pressure for any time, $t$, using the Friedlander equation, and the total blast load is then determined [4-8].

CONWEP was designed for air blast pressure and consequently, does not provide the correct pressure loading on a structural surface when the blast from a landmine throws soil at the surface, which increases the blast load on the structure significantly. To determine the blast associated loads on the surfaces blasted both by soil and air, the BCMS tool set uses CONWEP as an interpolator routine. This CONWEP module is used in the Tier 1 and Tier 2 simulation. In Tier 3 through Tier 5, a CONWEP routine is built in the LS-Dyna package.

The second module in the BCMS tool set is the scale-factors-table calculator (SFTC) which is developed based on a semi-empirical model [4-8]. By using extensive landmine live fire experimental data, the SFTC computes specific impulse as a function of standoff, radial distance, charge weight, and other parameters for a plate parallel to the ground. The SFTC then compares the calculated specific impulse (for landmine, i.e. includes the soil) with the one predicted by CONWEP (only for air) and generates, as a function of radius and standoff, a table with correction factors that are used in CONWEP/ LS-DYNA to generate realistic *soil* blast loads. The output of the SFTC is a scale factors table (for a given explosive mass, and soil) that provides the scale factors as a function of standoffs and radial distances.

The third BCMS module is LoadDyna that is developed using FORTRAN90, and uses the scale factor table generated by SFTC to compute the loading scale factor being passed to CONWEP (as an LS-DYNA keyword) to produce a realistic load on every segment of the mesh that is being affected by the blast. LoadDyna starts by reading the files rigidwall_planar.k, load_blast_enhanced.k, run.k, DepthOfBurial.dat, and BlastPipelineSettings_loads.dat, which provide the software, respectively, the following

information: 1) The up direction, 2) Explosive mass and position, 3) Units information, 4) Depth of burial of the charge, 5) Some default settings like scale factors for surfaces placed out of bounds of the scale factor table or the name of the file that contains the scale factors table.

LoadDyna then reads the scale factors table file and the file with the segments directly exposed to soil, name as mesh_lit_elements.k and the mesh file with the elements only exposed to air blast, named as mesh_shaded_elements.k. A segment in LS-DYNA is an oriented surface defined by three or four nodes. The order of the nodes defines, through the right-hand or corkscrew rules, the normal of the segment. Finally LoadDyna reads the geometrical mesh (mesh.k) data, specifically only the node coordinates to identify the position of each of the four nodes of a segment.

LoadDyna computes for each segment its center and then the standoff and radial distance from the explosive to the center of the segment. With the standoff and radial distance LoadDyna determines the scale factor to be used from the scale factor table and generates a keyword *load_blast_segment with the nodes of the segment and the scale factor. The outputs of this utility routine, LoadDyna, are placed in two files, the file load_blast_segment_direct.k with the segments impacted by soil and the file load_blast_segment_indirect.k for the segments only hit by the air blast.

LoadDyna additionally generates two more files for debugging purposes: bin_seg_set.k and load_segment_set.k. The file bin_seg_set.k contains sets of segments that have been binned according to their scale factor. That is to say, the segments in a set all have the same scale factor. The file load_segment_set.k assigns the appropriate scale factor to the set. These two files, together with the mesh file, when loaded in LS-PrePost, allow a visual inspection of the loaded surfaces to check if the model is working correctly.

## VALIDATION METHOD

In computational modeling and simulation (M&S), the performance predicted by using a model will only have some bearing on the real system if the model is a good representation of the simulated phenomena. Of course, what constitutes a good model is subjective, but from a performance modeling point of view, our criteria of good models will be based on how accurately the performance predicted by the model corresponds to the results obtained from real live-fire experiments.

By its nature a mathematical model of an underbody blast event is more abstract than the whole event the model represents (even a simulation model). Viewed in one way, abstraction and assumptions are made in the model development, which eliminates unnecessary detail and allow engineers to focus on the key elements within the system which are important from a performance point of view; viewed in another way, these assumptions and abstractions introduce inaccuracy. Some degree of inaccuracy may be necessary, desirable even, to make the model solution more efficient. Inevitably some assumptions must be made about the system in order to construct the model. However, efforts have to be made to validate the accuracy of the developed model.

In order to validate the AVM blast modeling and simulation tool set, three case studies are presented here, each with different complexity. Results from the simulation and live-fire test data are compared

In all these live-fire tests, the jump height of the target structure is recorded by using either high speed cameras or a string pot. A simple projectile motion equation was used to calculate velocity by using the obtained maximum jump height. If the air resistance is negligible during the event, the initial velocity of the target structure can be determined using the following equation:

$$V = Sqrt(2gh) \tag{1}$$

where $g$ is the gravitational constant and $h$ is the maximum jump height.

The initial velocity value obtained using equation (1) is the maximum velocity of the target object, and is then used to calculate the total impulse imparted to the target structure. In these presented experimental cases, the travel of the test structures is essentially a vertical launch, the total impulse of the tested structure is obtained based on simple ballistic trajectory physics using the following equation:

$$I = mV \tag{2}$$

where: $\boldsymbol{I}$ is the structure impulse, $m$ is the total mass of the tested structure plus all associated fixtures.

In addition to the kinematics of the tested structure, the dynamic and permanent deformations of the target structures are also recorded for the BCMS tool validation.

## VALIDATION CASES

In order to validate the above described AVM blast tools, three series of live-fire tests were used, investigated, analyzed and presented here in this paper.

### *Case 1: Rigid Plate Test*

The first case used in the analysis is a rigid plate test, which is an ideal test setup to validate Tier 1 blast simulation. To validate the AVM blast modeling and simulation (M&S) tool set initially, it is better to use a

simplified structure to reduce the approximations such that the focus is on the blast loading. The first series of simplified physical tests are conducted by using a rigid plate standing above a buried charge as shown in Fig. 1[5]. The steel plate is very thick and its deformation during an underbody blast load is negligible. No instrumentation is equipped with the plate. The objective of this series of tests is to validate the mine blast loading to the plate by using the plate kinematic movement, such as impulse and velocity. The plate velocity and maximum flight height are recorded by using high speed camera. For this type of test, the Tier 1 AVM blast modeling and simulation Tier 1 is most appropriate.

The charge is placed in the center of the circular plate with a burial depth of 2 inches. Two different charge masses are used in two different series of tests. Five blast tests of flat plates were performed for case 1. Three of these were detonated with Charge-Low, and the other two were detonated with Charge-High. The actual air filled void (AFV) in each test bed was calculated as follows. First, the dry density and water content are measured at 12 different locations in the test bed, and the average is used in the analysis. The maximum height of the rigid plate travel (also called jump height) is obtained from the test data, and the maximum velocity of the rigid plate is then calculated by using equation (1). The average maximum initial plate velocity, based on the measured plate jump height, is 18.1 m/s, and is listed in Table 1.

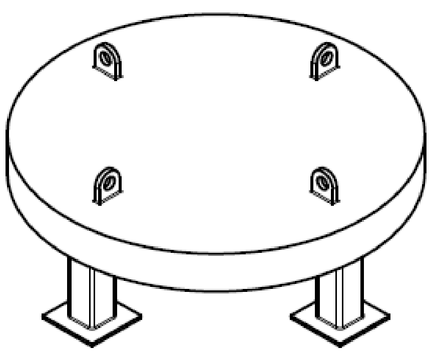

**Fig. 1**: Rigid plate test setup

### *Case 1: Analysis*

The live fire test using a rigid plate is modeled as shown in Fig. 2.

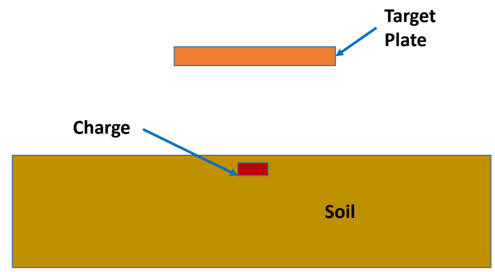


**Fig. 2**: Rigid plate blast model

The rigid plate model is automatically generated by using the BCMS tool sets, and the model created by using Tier 1 option is shown in Fig. 3. In addition, the same test setup was also used to validate the improvement of Tier 3 and 4 predictions. When using Tier 3 or 4 option, the finite element (FE) model automatically created by using BCMS tool set is shown Fig. 4. It is obvious that the FE model quality using a higher tier option in the BCMS tools set are much better in element quality. The test case were simulated by using the AVM blast tool kit using Tier 1 through Tier 4 options and their results are shown in the Table 1. The estimated plate jump height is 12.73 meters. The assessment of a vehicle with different mass under the same test condition is plotted in Fig. 5. The maximum plate initial velocities estimated by using AVM BCMS Tier 1 through 4 level of assessment accuracy are also listed in Table 1. It can be seen from Table 1 that the differences between the simulation and test are, for Tier 1, through Tier 4 respectively, 16.6%, 13.8%, 13.8% and 11.6% for the charge cases.

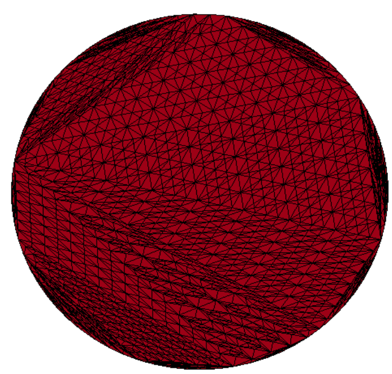

**Fig 3** Rigid plate model created by using BCMS Tier 1

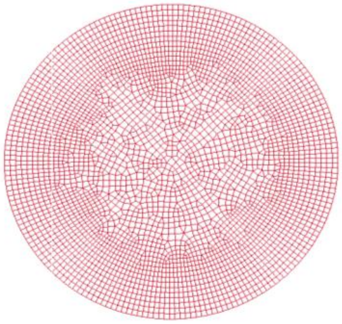

**Fig 4** Rigid plate Model Generated by Using BCMS Tier 3 and Tier 4

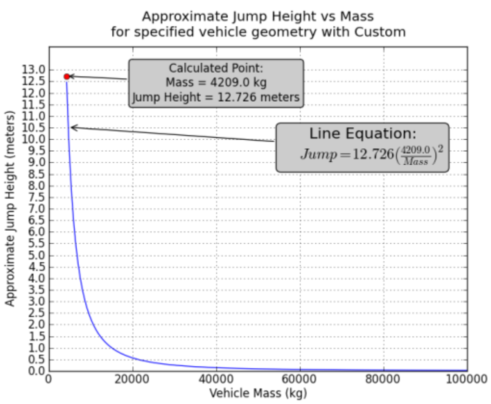


**Fig. 5** Predicted jump height of the rigid plate by using Tier 1 Analysis

**Table 1:** Rigid plate velocity Comparison for Low Charges

| | Test | M&S | Diff. (%) |
|---|---|---|---|
| BCMS T1 | 18.1 | 15.1 | -16.57 |
| BCMS T2 | 18.1 | 15.6 | -13.81 |
| BCMS T3 | 18.1 | 15.6 | -13.81 |
| BCMS T4 | 18.1 | 16.0 | -11.60 |
| ALE | 18.1 | 17.4 | -3.87 |

In summary, the BCMS tool suite can predict the rigid plate kinematics during a mine blast event with good accuracy. The prediction of a high fidelity FE model is also listed in Table 1, with an accuracy of -3.87% [5], which is very accurate prediction that can be achieved in modeling and simulation. But the CPU time to complete such a simulation is about 20 hours using 32 CPU, compared with about one hour or less using the BCMS tool suite, not to mention the extra time is needed to develop such a high fidelity model.

### *Case 2: Flexible Plate Test*

The second series of simplified physical tests use a thinner stainless steel plate at the very bottom with concentrated mass on its circumferential edge as shown in Fig. 6 [5]. The purpose of this test configuration is to measure the structural deformation from the combined blast and soil loading. During physical tests, two different charge sizes are used in this series of tests. Since the main deformation plate doesn't contact with any other structure, this series of live-fire tests are used to validate AVM blast modeling and simulation tool Tier 2, Tier 3, and Tier 4. It is anticipated that the prediction in Tier 2 and Tier 3 will be very close. This is because there is only one deformation plate in the structure, and not contacts involved in the event.

Like the test series of the rigid plate test, the charge is located at the center of the plate, with a burial depth of 2 inches. In this case, two blast tests of flat plate and its holding fixture were performed. They were detonated with Charge-Low. The actual AFVs in the test beds were calculated, respectively, as 12.2% and 12.3%. Fig. 7 shows the blast test set-up. After a blast test, the permanent deformations at the top surface of the plate center and the mid-point are measured.

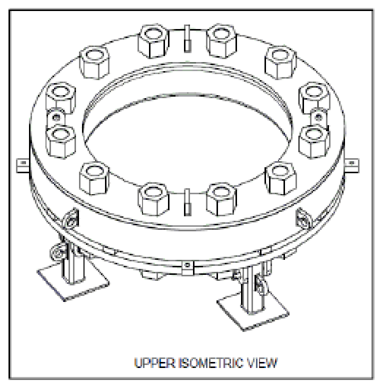


**Fig. 6:** Flexible plate test setup

**Table 2:** Flexible plate deformation results

| | Test | M&S | Diff. (%) |
|---|---|---|---|
| BCMS T2 | 22.9 | 19.8 | -13.54 |
| BCMS T3 | 22.9 | 19.8 | -13.54 |
| BCMS T4 | 22.9 | 21.5 | -6.11 |
| ALE | 22.9 | 24.8 | 8.30 |

***Case 2: Flexible Plate Analysis***

For comparison with the blast tests, models are created by using the BCMS tool set as shown in Fig. 7, and used in the AVM blast models. The deformation at the end of the 15ms simulation is treated as the permanent deformation of the plate. Such deformations at the plate center and mid-point can be extracted by the LS-DYNA Pre- & Post-processor (LSPP). Fig. 8 displays the simulated permanent deformations of the plate. The deformed overall shape matches very well with the test. The maximum plate permanent deformation estimated by using AVM BCMS Tier 2 through 4 level of assessment fidelity are also listed in Table 2. It can be seen from Table 2 that the differences between the simulation and test are, for Tier 2/3, and Tier 4 respectively, -13.54%, and -6.11% for the tested threat conditions. All deformations estimated by using the three fidelity models in the table are the deformation value at the end of the simulations, which are assumed to be permanent deformation.

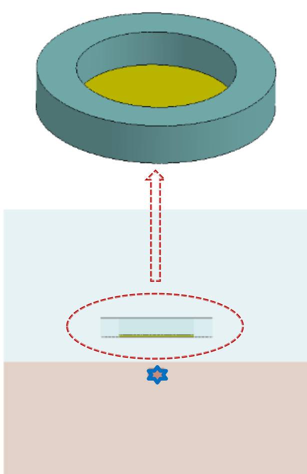

**Fig. 7**: Flexible plate blast model

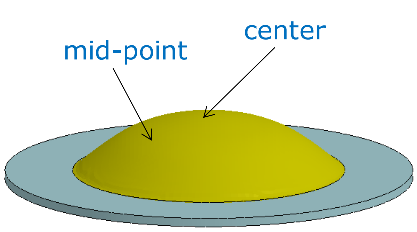


**Fig. 8**: Flexible plate simulation results

A high fidelity FE model was also generated to simulate the same tested threat condition [5]. With a high fidelity FE model, the predicted plate permanent deformation is 24.8 cm., with an accuracy of 8.3% (as listed Table 2, under the title row of ALE).

In summary, the estimation of the deformation in this testing series are very close to the live fire testing measurements. The accuracy of the BCMS models are comparable to the high fidelity models.

***Case 3: Blast Box***

A live fire blast test using a simplified vehicle structure name blast box was designed and conducted in the AVM effort in order to test the entire AVM tool chain from a blank screen to a finished product. The test fixture in the configuration, Blast Box, is shown in Fig. 9, which is made of RHA plates, and weighs nominally 5831 kg. Panels are welded together with specially-prepared panel edges to form the V-hull. In order to reduce weight and give the V-hull structure stiffness, two reinforcement trusses are added inside the hull. The blast V-hull was bolted at the center of the underside of the fixture using sixteen 1-inch diameter bolts.

**Fig. 9** Blast box structure

The Blast Box is a very challenging test for fabrication and assembly because it contained a large number of parts and thus very complicated assembly and welding instructions.

In the design process of the Blast Box, the AVM HuDAT tool was employed to create the edge preparation on the plates and the welds for the blast V-hull. The HuDAT tool relied on a soap bar framework for the design process, and thus required an enclosed hull. The blast box model is not strictly an enclosed hull, and as such, extra panels were

created to enclose the buck. After HuDAT ran, the extra panels were removed from the assembly. The designed Blast Box for live-fire blast testing is illustrated in Fig. 9.

The AVM treatment of bolts was determined to be incompatible with the blast test bench. The AVM treatment calls for bolts to be treated as individual components. The blast test bench did not model bolts as individual components, but rather treated adjacent plates with aligned holes as being bolted together. As such, whereas the bolts were included as components to generate the assembly instructions in iFAB, they were removed from the model described in the following sections.

### *Test Setup*

After fabrication, the blast box was delivered to Southwest Research Institute (SwRI) for blast testing to validate the AVM blast performance predictions. The live-fire blast test was conducted using the SwRI Landmine Test Fixture as shown in Fig. 9 [4].

The test consisted of the detonation of a small-scale simulated landmine charge, buried in soil, resulting in an impulse load on the blast box. The blast causes the up-lifting of the entire fixture/blast box assembly. Instrumentation is used to measure the jump height and acceleration of the fixture as it responds to the blast.

**Fig. 10** Live fire blast test of the blast box structure for AVM Program.

### *Charge*

The typical threat charge to the underbelly of an armored vehicle is a buried landmine. A bare Composition C4 charge was used as a surrogate for a typical landmine. The mass of the charge was chosen based on pre-test simulation that predicts the blast box jump height. The bare charge was made by compacting the C4 into a 11.75 cm (4-5/8-inch) diameter mold. The resulting charge shape was a cylinder with a nominal height of 3.97 cm (1-9/16-inches). The charge cake is shown in Fig. 11. Once the charge is removed from the mold, it is tightly wrapped in electrical tape so that it holds its shape. A make-shift handle, made from electrical tape, is added to assist the blaster during the placement of the charge for the test. An RP-83 EBW detonator, used to initiate the explosive, was centered on the bottom of the charge.

### *Soil*

The explosive charge was positioned in an engineered soil pot for this test. The soil pot was constructed using a 36-inch diameter section of cardboard tubing (Sonatube). The Sonatube assembly measured 34.29 cm (13.5-inches) tall and had two 1.91 cm (¾-inch) plywood disks fastened in place to form a circular floor. A third piece of plywood, measuring 101.6 cm (40-inches) square, was screwed to the bottom to complete the soil pot assembly. Raba-Kistner Engineering constructed the desired soil mixture (50% clay/50% sand) in their lab and then filled the soil pot in three nominally-equal steps (about 10.16 cm (4-inches) at a time). For each filling step, they obtained the correct moisture content by adding water as required and the correct density by compressing it with a hand-tamper. The final height of the soil was 30.48 cm (12-inches). The target parameters were a density of 120 to 124 pcf and a moisture content of 13% to 14%. To maintain the proper moisture content prior to its use in the test, the pot assembly was sealed with plastic sheeting promptly after it was prepared. The soil pot was made the day prior to test day to further minimize moisture loss in the soil. Prior to the test, a cavity just large enough for the explosive charge was generated by hand in the center of the soil pot. After excavation, charge was placed in the cavity and covered with 2-inches of the engineered soil that had been pulled-out during the cavity excavation. The blaster did his best to pack the soil above the charge to the same consistency as that of the adjacent parts of the soil pot (Fig. 11).

**Fig. 11** Charge at the center of soil pot

The fabricated blast box was tested at Southwest Research Institute with the following test setups:

- Charge = Composition C4,
- DOB = 5.08 cm,
- Standoff = 30.48 cm,
- Soil was 50% Sand/50% Clay,
- Soil Density = 123.0 pcf (average),
- Soil Moisture Content = 11.8% (average),

The charge depth of burial (DOB) was the distance from the top of the C4 charge to the surface of the soil. The plate standoff was the distance between the top surface of the soil to the lower peak of the V-shaped blast box bottom. The soil was inserted into the pot assembly in three steps or "lifts," each one being approximately 10.16 cm (4-inches) thick. The moisture content varied for each of the lifts, as shown in the report; the average value is provided in the summary above.

Table 3. Blast Box test results

| Measurements | Test Results |
|---|---|
| Acceleration (g) | 177.2 |
| Jump Height (cm.) | 4.39 |
| Velocity (cm/s) | 93.0 |
| Total Impulse (kN-s) | 5.62 |
| Permanent V-hull def. (cm.) | 10.31 |

Table 3 summarizes the measurements during and after the live-fire test. The data provided includes the jump height measured using the string pot gauge in this test. The maximum jump height is used to derive the box initial launch velocity in the table by using the equation 1 stated in the earlier section.

**Fig. 12** Post-test Dynamic Deflection (Pin) Gauge

The estimated blast box initial velocity, the masses of the blast box and test fixture were then used to calculate the total impulse imparted in the mine blast threat condition. The calculated initial velocity of impulse of the blast box is listed in Table 3.

**Fig. 13** The deformation of the V-Hull after the live fire test shown in top view

Also included in Table 3 is the value for dynamic deflection and permanent deflection. The dynamic deflection value of the floor is calculated based on the length of the shortest pin of the deflection pin gauge, as illustrated in Fig. 12. The permanent deflection value is the post-test measurement of the deflection of the blast box after it was removed from the test fixture, as shown in Fig. 13 from top view and in Fig. 14 from bottom view. It was measured by placing a straight-edge along the side edges of the blast box assembly and measuring the maximum deflected distance to the peak of the deformed area.

**Fig. 14** Blast box V-hull permanent deformation shown in bottom view

### *Case 3: Blast Box Analysis*

The LS-Dyna model is built by using the AVM Blast M&S tool. The model is illustrated in Fig. 15. In this model, all welding seams and heat affected zones of the welding process are simulated by welding components marked by different colors. In the welding components, the material strength is reduced to 60% of the base materials. The test setup was modeled by using BCMS tool suite, with tier 4 fidelity of accuracy. The model predictions of jump height, velocity, and impulse and V-hull deformations are listed in Table 4. The initial maximum velocity of the blast box and test fixture is measured at the testing fixture top center in the model created by the BCMS tool suite. Based on this initial velocity, the test fixture jump height and total impulse is calculated by using equations (1) and (2) described earlier in this paper. The permanent V-hull deformation is measured at the middle of the center V-hull tip, using the test fixture top rigid plate center as a reference point.

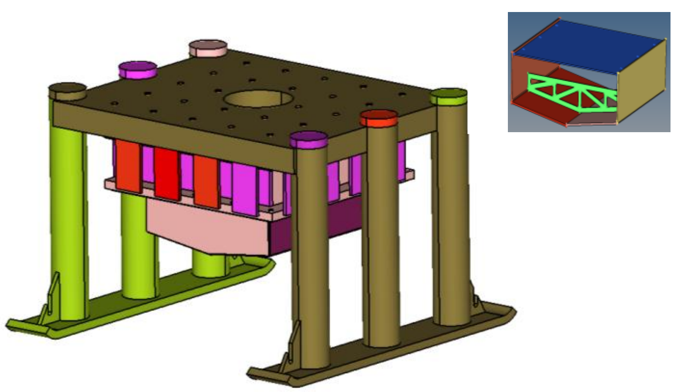

**Fig. 15** The FE model of the blast box and text fixture

Table 4: Comparison of acceleration, jump height, velocity, impulse, and permanent deformation of V-hull

| Measurement Items | Test | Tier 2 | Tier 3 | Tier 4 |
|---|---|---|---|---|
| Jump Height (cm) | 4.39 | 3.59 | 3.59 | 3.31 |
| Velocity (cm/s) | 93.00 | 83.95 | 83.95 | 80.62 |
| Total Impulse (kN-s) | 5.62 | 4.75 | 4.75 | 4.56 |
| Permanent V-hull def. (cm) | 10.31 | 15.19 | 15.19 | 17.52 |

Table 5: Estimation Errors of BCMS Tool: Tier 2 & Tier 3

| Measurement Items | Test | Tier 2 & 3 | Diff. % |
|---|---|---|---|
| Jump Height (cm) | 4.39 | 3.59 | -18.30 |
| Velocity (cm/s) | 93.00 | 83.95 | -9.73 |
| Total Impulse (kN-s) | 5.62 | 4.75 | -15.48 |
| Permanent V-hull def. (cm) | 10.31 | 15.19 | 47.30 |

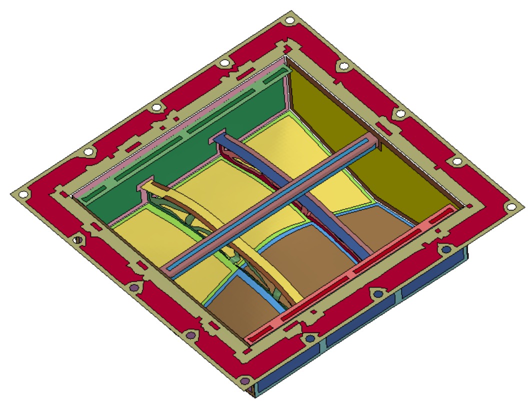

**Fig. 16** BCMS tool predicted deformation of the V-Hull shown in top view and the truss deformation

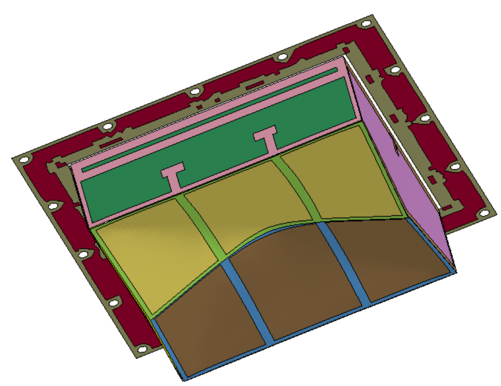

**Fig. 17** AVM M&S tool predicted deformation of the V-Hull shown in bottom view

Table 6: Estimation Errors of BCMS Tool: Tier 4

| Measurement Items | Test | Tier 4 | Diff. % |
|---|---|---|---|
| Jump Height (cm) | 4.39 | 3.31 | -24.67 |
| Velocity (cm/s) | 93.00 | 80.62 | -13.31 |
| Total Impulse (kN-s) | 5.62 | 4.56 | -18.86 |
| Permanent V-hull def. (cm) | 10.31 | 17.52 | 69.89 |

The permanent deformation of the V-hull predicted by using the BCMS tool suite is illustrated in Fig. 16 from the top view. The same V-hull deformation can be shown in the bottom view as in Fig. 17. By comparing these two figures with Figs. 13 and 14, it is concluded that the V-hull global deformation is captured in the model described. In the live fire test, there is no failure in the blast box, either on the base material panels or on the welding seam. The BCMS models in all three Tier fidelity predicted the same performance.

For the estimates using the Tier 2 and Tier 3 models created by BCMS tool set are compared with the measurements in the live fire test. The prediction errors are also calculated and listed in the same table. The initial jump velocity was under estimated 9.73% as listed in Table 5. Due to this prediction difference, the test fixture jump height and total impulse are all under estimated with an amplification factors as indicated in the equations (1) and (2). The V-hull deformation is significantly over estimated by using these two models with an error up to 47.3%, as listed in the same table.

Table 6 listed the predictions by using Tier 4 model of the same testing setup created using the BCMS tool suite. The prediction errors of the maximum initial jump velocity and V-hull deformation are -13.31% and 69.89% respectively. Accordingly, the jump height and total impulse are all under estimated. It is surprised that the prediction errors are more than those predicted in the Tier 2 model and Tier 3 model. All the errors are believed to be from the over estimation of the underbelly V-hull deformation.

In this more complicated structure cases, the accuracy of the BCMS tool suite predictions are decreased.

## DISCUSSION AND CONCLUSIONS

This paper presents three series of live fire testing cases to validate the AVM Blast Computational Modeling and Simulation (BCMS) tool suite. The accuracy of the AVM Blast M&S Tool suite is demonstrated by comparing the simulated velocity/ deformation results with the test measurements. This validation effort shows:

(1) For the simplified structure, like the rigid plate, the AVM Blast M&S Toolset prediction agrees well with the live fire test measurements. The errors in the plate maximum initial jump velocity are 16.57%, 13.81%, 13.81% and 11.6% respective for Tier 1 through Tier 4 models, which is a very good correlation with the tests.

(2) In the deformable plate test cases, the estimation of the deformation is very close to the live fire testing measurements. The accuracy of the BCMS models are comparable to the high fidelity models in the same testing setup.

(3) In a more complicated structure case like the blast box, The initial jump velocity of the test setup is estimated using Tier 2 and Tier 3 models generated using BCMS tool suite with reasonable accuracy. For the same testing case, the Tier 4 model prediction of the initial velocity is 13.3% under estimated which is more than those predicted in the Tier 2 and Tier 3 models. The hull deformation prediction errors of Tier 2&3 as well as Tier 4 are 47.3% and 69.89% respectively. With the more complicated structure, the accuracy of the response predictions using AVM Blast M&S Toolset is decreased, which indicates improvements are needed if the tool set is used for the survivability assessment of full ground vehicle systems.

It is believed that the distribution of the blast load around the charge center line is too concentrated at the center. This hypothesis can be seen in the deformation of the V-hull, which is a more deep deformation compared the post-test hull shape in the live fire test case. The same phenomena is also observed in the deformable test case. The concentrated loading caused the over-estimation of the structure deformation. Because the under-belly structure deformation is over estimated, the more energy is consumed on the underbelly structure, and the jump height of the structure is under estimated. This hypothesis needs to be further validated by using live fire tests and more detailed studies.

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